

“Closed-loop” analysis of a thermo-charged capacitor

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Abstract

In this Letter, an explicit application of conservation of energy and zero net work principle around a closed path (“closed-loop” analysis) is carried out on a thermo-charged capacitor at equilibrium with ambient heat at uniform temperature. This analysis corroborates the results of previous studies [*Phys. Lett. A* 374 (2010) 1801, *Physica A* 390 (2011) 481] that a potential drop ΔV does actually occur at capacitor terminals. Finally, a conventional photoelectric emission experiment is proposed to indirectly test thermo-charged capacitor functioning.

Keywords second law of thermodynamics · thermionic emission · contact potential · diffusion · capacitors · vacuum tube · photoelectric emission

1 Introduction

In a series of papers, the first one of which dates back to 2010, I theoretically investigated the possibility of harnessing energy from ambient heat at uniform temperature. I introduced what I have then called “thermo-charged capacitor” along with a mathematical model of its alleged functioning. Let me briefly review its design to set the stage for what is going to be the topic of the present paper. For those interested in further details, refer to [1, 2, 3, 4, 5].

A thermo-charged capacitor (TCC) is vacuum capacitor (spherical or flat) spontaneously charged harnessing the heat absorbed from a single thermal reservoir at room temperature.

In Figure 1 a sketch with the essential features of a TCC is given. Electrode A is made of metallic material with relatively high work function

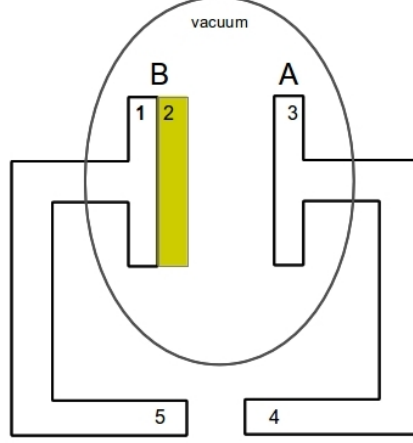


Figure 1: Sketch of a vacuum thermo-charged capacitor: electrode A is made of a high work function metal (3 – 4), electrode B is made of a high work function metal (1 – 5) coated with a layer of semiconductor Ag–O–Cs with low work function (2). Work functions are such that $\phi_{1-5} = \phi_{3-4} > \phi_2$.

($\phi_A = \phi_{3-4} > 1 \text{ eV}$). Electrode B is made of the same conductive material as A , but it is coated with a layer (2) of semiconductor Ag–O–Cs, which is known to have a relatively low work function ($\phi_2 \lesssim 0.7 \text{ eV}$, but $\phi_{1-5} = \phi_A$). When TCC is properly shielded from light or other electromagnetic disturbance (natural and man-made e.m. waves, cosmic rays and so on), only the energetic tail of black body radiation originating from ambient heat is responsible for the thermionic (actually, “photoelectric”) emission at electrodes A and B . In such a design, the thermionic fluxes from A to B and from B to A are different, the latter being greater than the former, at least at the beginning of the charging process.

A fraction of the electrons thermionically emitted from electrode B are definitely collected by (very low emitting) electrode A , creating a macroscopic difference of potential ΔV between A and B (for the equations governing the thermionic emission charging process, see [1, 2]). At first, such a process is unbalanced, the flux from electrode B being greater than that from A , but later, with the increase of potential ΔV , the two-way *effective* fluxes tend to balance each other exactly. A dynamical equilibrium of charges (space charge) between the electrodes is eventually attained. Remind that in vacuum the thermionic emission can be seen as a ballistic ejection process.

In paper [2] I also showed that the experimental measurement of ΔV

between 4 and 5 is not an easy task: an electrometer with extremely high input impedance (several $T\Omega$) is needed since output currents are expected to be of the order of 10^{-14}A .

Legitimate doubts may arise that even if the mathematical treatment made in those papers were unexceptionable, it might be incomplete: for some hidden reasons there might be no potential drop at capacitor terminals (4 and 5), leaving out the measurement problem.

Since the publication of the cited papers no one seems to have put forward any criticism. This notwithstanding, I myself devoted some time and energy to address at least two possible objections to the above design and functioning.

The first one is related to the presence of a Schottky rectifying junction inside electrode B (between metal and Ag–O–Cs layer), which appears to prevent any charge displacement from metal to semiconductor, and thus to prevent any current flow across the whole capacitor when terminals 4 and 5 are shorted (or, equivalently, zero voltage drop between 4 and 5 when they are left open). Actually, this objection has already been addressed in the second paper on TCC, and the interested reader could easily go through the original source [2].

The second objection has been the topic of an Addendum to the second paper on TCC [2]. Since it is important for what we shall see in the following Section, let me resume below its key aspects.

As already noted, the contact surface between the metallic part 1 of electrode B and its semiconductor layer 2 (Ag–O–Cs) is a metal/n-type semiconductor junction (Fig. 1, region 1 – 2). Across such a junction a contact potential builds up, equal to the differences between the two work functions divided by the electronic charge, $\Delta V = \frac{\phi_1 - \phi_2}{e}$. This potential is the result of charge diffusion across the junction 1 – 2 as soon as the two materials are physically joined. The junction is thus the region where, at equilibrium, a balance between electrostatic and diffusive (thermally driven) forces is attained.

In almost all textbooks it is said that a voltage drop builds up not only across the contact surface 1–2, but instantaneously also between the surfaces at the free ends of the joined materials (free surface of semiconductor 2 on one side and free surface 5 of the metal on the other, but also free surface of semiconductor 2 and free surface 3 of electrode A , when terminals 4 and 5 are shorted, see Fig 1).

Note that this voltage drop is not intended to be that generated by thermionic emission of electrons from B to A . It is intended to originate from an overall charge displacement in the bulk of electrode B across the junction as soon as the materials 1 and 2 are physically joined. To my

knowledge, no textbook or published paper on the subject clearly explains how and why these charges collectively and macroscopically move inside the bulk of electrode B across the junction so as to charge the metal (1 – 5, or 1 – 5 – 4 – 3 when terminals 4 and 5 are shorted) negatively and semiconductor 2 positively. This voltage drop is of the same magnitude of the contact potential.

All this is usually explained appealing to a supposed straightforward application of the Kirchhoff's second (loop) rule. If this were true, then it would prevent any net current flow across the whole capacitor when the two electrodes are electrically shorted at their free ends (terminals 4 and 5), so as to establish a closed circuit. As a matter of fact, in order to reach electrode A , any electron escaping electrode B would need the same energy needed by an electron escaping electrode A to reach electrode B . B -electrons need an energy equal to $\phi_2 + e\Delta V$, since they must be ejected (required energy ϕ_2) and then they have to overcome the potential drop ΔV instantaneously generated between 2 and 3 due to the contact between 1 and 2, (energy equal to $e\Delta V$). A -electrons need ϕ_3 (only the energy to be ejected). But, since $e\Delta V = \phi_1 - \phi_2 = \phi_3 - \phi_2$, B -electrons need $\phi_2 + e\Delta V = \phi_3$.

I have explicitly shown in another paper [3] that no electric field, and thus no voltage drop, builds up between the surfaces at the free ends of two materials with different work functions (namely, between 2 and 5, or equivalently between 2 and 3, when terminals 4 and 5 are shorted) when the materials are physically joined at one end (region 1 – 2).

In that paper I performed the following “closed-loop” analysis, namely I made an explicit application of the *path-independence* law and/or Kirchhoff's loop rule. The physical principle at the basis of these two laws is the more fundamental law of conservation of energy.

At equilibrium, conservation of energy demands that a test electronic charge e conveyed around a closed path γ in the device bulk of Fig. 2 (which equivalently represents either the sole electrode B of Fig. 1 or the whole TCC of Fig. 1 if terminals 4 and 5 are shorted), through physical junction J-I (1 – 2) and gap J-II between 2 and 5, if Fig. 2 is intended to be the sole electrode B , or between 2 and 3 if Fig. 2 is intended to be the whole TCC of Fig. 1 with terminals 4 and 5 shorted, must undergo zero net work from *all* the forces present along the path. Mathematically, we must have,

$$\oint_{\gamma} dW_{tot} = 0. \quad (1)$$

Note that for this analysis I **completely neglect** the thermionic emissions of all the materials. I am focusing only on the physical process across the contact junction 1 – 2 at equilibrium.

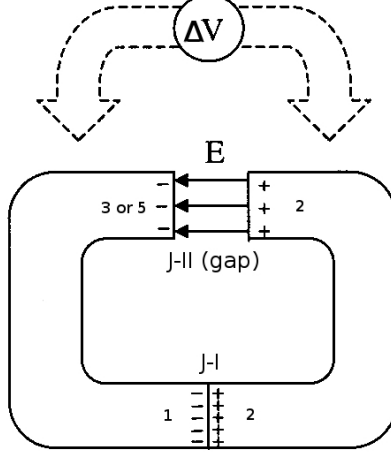


Figure 2: This figure equivalently represents either the sole electrode B of Fig. 1 or the whole TCC of Fig. 1 if terminals 4 and 5 are shorted. J-I is the physical junction 1 – 2 and J-II is the gap between 2 and 5, if this figure is intended to be the sole electrode B , or between 2 and 3 it is intended to be the whole TCC of Fig. 1 with terminals 4 and 5 shorted. Work functions are such that $\phi_1 > \phi_2$.

At equilibrium, the only two regions where forces are allowed to be non-null are the J-I and J-II regions. An electric field elsewhere in the device bulk (other than in the contact region) would generate a current, which contradicts the assumption of equilibrium. When the test charge e crosses J-I, it is subject to the built-in electric field force $e\mathbf{E}_{bi}$ and to the diffusion force \mathbf{F}_{diff} . This “force” is the thermally driven force responsible for the establishment of the contact potential at J-I. We know that at equilibrium $e\mathbf{E}_{bi} = -\mathbf{F}_{diff}$ and that \mathbf{F}_{diff} is different from zero and constantly present, otherwise \mathbf{E}_{bi} would soon drop to zero, thus,

$$0 = \oint_{\gamma} dW_{tot} = \int_{\mathbf{J-I}} (e\mathbf{E}_{bi} + \mathbf{F}_{diff}) \cdot d\vec{\gamma} + \int_{\mathbf{J-II}} dW_{ext} = 0 + \int_{\mathbf{J-II}} dW_{ext}. \quad (2)$$

In the J-II gap there are no diffusion forces, since it is a vacuum gap, and eventually we have,

$$0 = \int_{\mathbf{J-II}} dW_{ext} = \int_{\mathbf{J-II}} e\mathbf{E}_{\mathbf{J-II}} \cdot d\vec{\gamma} = e|\mathbf{E}_{\mathbf{J-II}}|x_g \rightarrow |\mathbf{E}_{\mathbf{J-II}}| = 0, \quad (3)$$

where x_g is the gap width.

In the following Section, I perform the same “closed-loop” analysis across the whole TCC by taking into account the thermionic emission between 2 and 3, and by considering the capacitor thermionically charged and at equilibrium (with terminals 4 and 5 not shorted). The outcome gives further support to the results of the cited studies that a potential drop ΔV does actually occur at the free ends (4 and 5) of a TCC.

2 Closed-loop analysis across a thermionically charged TCC

I apply the energy conservation analysis made in [2, 3] across the whole thermionically charged capacitor at equilibrium. In what follows reference is made to Figure 3.

Figure 3 shows a charged TCC at equilibrium (with non shorted terminal leads). As in Fig. 1, region 1 – 2 is the depletion region at the metal/Ag–O–Cs junction. Dots in the vacuum region (region 2 – 3) represent the space charge electrons which, at equilibrium, are continually emitted and re-absorbed by electrode surfaces (the main part come from the Ag–O–Cs layer on electrode *B*). Part of the electrons emitted by electrode *B* have been definitely absorbed by electrode *A*. These are represented by the minus-signs on electrode *A* and are responsible for the thermionically generated potential drop between 2 and 3 [1, 2].

Once again, conservation of energy demands that a test electronic charge e conveyed around a closed path γ in the device bulk of Fig. 3, through regions 1 – 2 (physical junction), 2 – 3 (vacuum gap) and 4 – 5 (open terminal leads) at equilibrium, must undergo zero net work from *all* the forces present along the path. At equilibrium, the only regions where the forces are allowed to be non-zero are 1 – 2, 2 – 3 and 4 – 5, and mathematically, we have,

$$\oint_{\gamma} dW_{tot} = \int_{1-2} dW + \int_{2-3} dW + \int_{4-5} dW = 0. \quad (4)$$

The integral $\int_{4-5} dW$ is equal to $e\Delta V_{ext}$, namely the voltage drop at the free ends of the thermo-charged capacitor, multiplied by the test charge e . The integral $\int_{1-2} dW$ has already been proved to be equal to 0 (previous Section and [2, 3]).

The point is then: is the integral $\int_{2-3} dW$ different from zero? I have already shown in the aforementioned publications that a voltage drop ΔV should arise inside the vacuum capacitor due to the thermionic emission

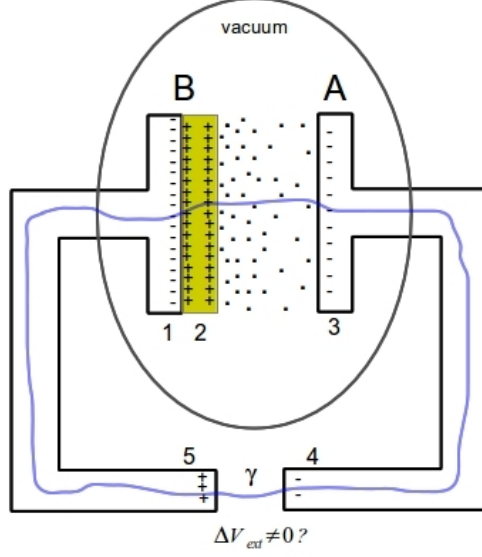


Figure 3: Charged TCC at equilibrium with ambient heat at uniform temperature (with non-shortened terminal leads 4 and 5). As in Fig. 1, region 1 – 2 is the depletion region at the metal/Ag–O–Cs junction. Dots in the vacuum region (region 2 – 3) are the space charge electrons which, at equilibrium, are continually emitted and re-absorbed by electrode surfaces. γ is the closed path traveled by the test charge e .

charging process and thus an electric field \mathbf{E}_{int} (equal to $\frac{\Delta V}{d}$, where d is the inter-electrode distance) should be present between the electrodes inside the capacitor (between 2 and 3).

Nevertheless, are we sure that a sort of compensating (thermally driven) diffusion force \mathbf{F}_{int} , similar to that present in the contact junction 1 – 2, is not present inside the vacuum capacitor cancelling out the internal electric force $e\mathbf{E}_{int}$? If this were the case, we would have,

$$-e\mathbf{E}_{int} = \mathbf{F}_{int} \quad (5)$$

and thus,

$$\begin{aligned}
\oint_{\gamma} dW_{tot} &= 0 + \int_{2-3} dW + \int_{4-5} dW = \\
&= \int_{2-3} (e\mathbf{E}_{int} + \mathbf{F}_{int}) \cdot d\vec{\gamma} + e\Delta V_{ext} = \\
&= 0 + e\Delta V_{ext} = 0. \quad (6)
\end{aligned}$$

This would mean that $\Delta V_{ext} = 0$, namely the TCC would have a zero voltage drop between its external leads.

Let me go into the possible nature of \mathbf{F}_{int} . As in the case of contact junction, this force could be seen as a collective and macroscopic manifestation of single microscopic actions on the electrons ejected by the thermionic surfaces (mainly, the Ag–O–Cs layer). At equilibrium, electrons are continuously emitted (due to the absorption of light quanta from black body radiation) and re-adsorbed by the surface of electrode B (the same process is going on also on electrode A but at a far smaller, negligible rate). The collective action of quanta absorption could be seen as a force acting in the opposite direction of \mathbf{E}_{int} : the field tends to pull the electrons just ejected from electrode B (and thus also the test charge e) back to electrode B . The force \mathbf{F}_{int} tends instead to push electrons (and thus the test charge e) away from electrode B .

In the following Section I put forward three arguments which suggest that \mathbf{F}_{int} is actually non-existent.

3 Discussion

In what follows I list three arguments, in increasing order of cogency, that appear to dismiss any concern about the possibility that \mathbf{F}_{int} really exists and cancels out the internal, thermally generated, field force \mathbf{E}_{int} :

- a) Cursory objection to \mathbf{F}_{int} : inside TCC there are no diffusion forces ($\mathbf{F}_{int} = 0$) since there is vacuum between electrodes A and B .
- b) Heuristic objection to \mathbf{F}_{int} : in [3] I have noticed that a kind of “force” \mathbf{F}_{diff} acting upon the electrons must exist in the depletion region, otherwise the built-in electric field \mathbf{E}_{bi} would go instantaneously to zero (there is a physical contact between metal and semiconductor in the junction). This close connection between \mathbf{F}_{diff} and \mathbf{E}_{bi} is expressed by the identity $\mathbf{F}_{diff} = -e\mathbf{E}_{bi}$. In a fully charged TCC at equilibrium, if

we could “switch-off” the thermionic emission, the field inside the capacitor would still be there (maybe only becoming more uniform since space charge would cease) since some electrons from electrode B have already been absorbed/collected by electrode A . Thus, we may heuristically conclude that, at equilibrium, \mathbf{E}_{int} and \mathbf{F}_{int} are not the one depending upon the other¹ and there would be no reason to assume that $\mathbf{F}_{int} = -e\mathbf{E}_{int}$ exactly. There is no strict cause/effect relation between \mathbf{E}_{int} and \mathbf{F}_{int} as in the case of the contact junction.

- c) Comparison with the behaviour of electrons in a photoelectric tube: given the possible microscopic explanation/origin of the force \mathbf{F}_{int} , this force would also be present on the active surfaces of a photoelectric tube² with electrodes immersed in and illuminated by diffused light and with non-shortcd terminals. This time, photoelectric emission comes into play. If we apply the same closed-loop analysis performed on TCC and admit the equivalence $\mathbf{F}_{int} = -e\mathbf{E}_{int}$, then we would have a zero voltage drop between the (open) external leads of an illuminated photoelectric cell. But this is experimentally not true.

Given a), b) and c), and the result of the closed-loop analysis performed in Section 2 with $\mathbf{F}_{int} = 0$, a voltage drop does actually occur at the free ends (4 and 5) of a TCC.

4 A conventional photoelectric emission test

Here, I want to draw the attention to an indirect but, from the experimental point of view, probably easier way to test the thermo-charging phenomenon. It is a further development of argument c). I briefly describe a conventional photoelectric cell (UV spectrum) with highly symmetrical lighting and show why it could be useful to indirectly test thermo-charged capacitor functioning.

The idea and the rationale behind the present proposal come from the following simple observation: if it is possible to extract energy from the plain (UV spectrum) photoelectric effect, why should not be possible in principle to extract energy (although to a very lesser extent) from the photoelectric effect generated by the high energy tail of the black-body spectrum (see Fig. 4) at a single temperature, provided that the device has two plates (anode and cathode) with different work functions?

¹The one does not exist *only* because of the other.

²The device depicted in Fig. 2 or Fig 3 could equally work as a photoelectric tube when illuminated by visible light.

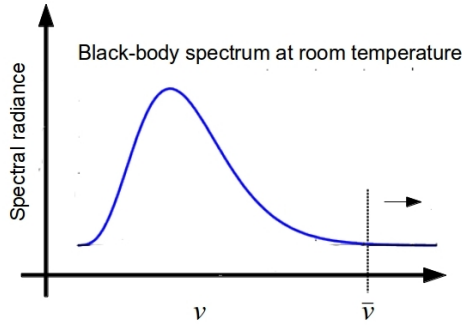


Figure 4: As already suggested in Section 1, any body in thermal equilibrium at any temperature T is surrounded by a bath of radiation in which the frequency distribution is given by Planck's formula. This formula puts no finite limit on the magnitude of the frequencies occurring; so that there will always be a frequency $\bar{\nu}$ present for which $h\bar{\nu}$ is greater than the work function of the body and thus triggering electron emission.

It could be objected that a UV spectrum photoelectric device works only when light impinges onto only one of the two plates, no matter whether they have different work functions, while in a “black-body spectrum” device both plates are inevitably affected by the same radiation (the device is immersed in the black-body radiation), no matter whether they have different work functions.

A relatively simple way to settle the issue (*experimentum crucis*) is to build a conventional photoelectric device (see Fig. 5) with equal parallel plates, same size but different work functions ($w_1 > w_2$), and to enlighten them both with the same amount of light, equal in frequency, intensity and geometry (for instance, by putting a point-like source of light right between the plates). If a photoelectric cell works with same UV light on both plates, it will also work with the high frequency tail of the black-body spectrum on both plates. If the system gets charged (one plate with positive and the other with negative charges due to excess electrons from plate w_2), the same will happen, although to a very lesser extent, with “black-body spectrum” devices, and thus with thermo-charged capacitors.

This would mean an indirect but clear confirmation that thermo-charged capacitor behaves as expected. And this will also dissipate all the objections to the thermo-charged capacitor theory concerning rectifying contact junction and contact potential difference.

It must be admitted that the experimental verification of this is not as simple as it appears to be at first sight. It is not simple to read a result as

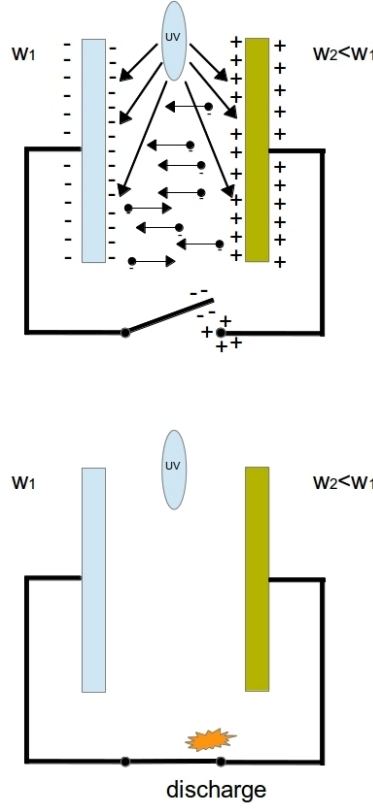


Figure 5: Schematic of a symmetrical photoelectric cell. Work functions w_1 and w_2 are such that $h\nu_{uv} > w_1 > w_2$ and thus photo-electrons from plate w_1 are fewer than those from plate w_2 . If it works, the above cycle can be repeated.

positive or negative. According to the theory, a negative result would be one in which no potential difference whatsoever is generated between the plates. But it is practically impossible to get zero voltage in a real experiment, thus how to set the threshold between denial and confirmation? A possibility can be to turn the plates 180 degrees around the central, point-like light source (left fixed) and see whether the voltage changes sign (or changes to a substantial amount) or stays almost the same. In the second case, there is room to believe that the photoelectric cell works also with UV light on both plates.

Obviously, a definitive answer to the above questions can only come from a carefully designed laboratory test. This notwithstanding, given what we

known about photoelectric effect and the simplicity of the setup in Fig. 5, it is difficult to believe that the device remains uncharged upon symmetrical UV illumination and that this cycle cannot be repeated.

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